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Parallel transport in a tokamak scrape-off layer

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1. Introduction

Sudden transient events – such as edge-localized modes (ELMs) – routinely occur in the tokamak edge during H-mode confinement. ELMs are plasma relaxations that cause a sudden drop in density and temperature of the pedestal plasma, leading to a significant loss of the stored plasma energy. Once the ELM-driven plasma pulse has crossed the magnetic separatrix, it travels mainly parallel to the magnetic field lines and ends up hitting the divertor plate, after a delay typically of the order of a few hundred microseconds.

In the present paper, the fully nonlinear parallel dynamics in the scrape-off layer is solved by means of a self-consistent kinetic model (Vlasov-Poisson equations), though collisions and effects due to plasma-surface interactions – such as secondary electron emission and recycling – are neglected. The Vlasov equation is integrated numerically using an Eulerian method, which guarantees a high resolution in velocity space, even in regions of low plasma density such as the sheaths [1].

The model is applied to the study of parallel transport during edge-localized modes (ELMs), with particular emphasis on the energy fluxes on the divertor plates. The numerical results are compared to analytical estimates based on a free-streaming model, and to numerical simulations performed using two different approaches: a particle-in-cell code [2] and a one-dimensional fluid code [3]. An interesting feature is the observation of an early electron energy flux, due to suprathermal electrons escaping the ions' attraction. In contrast, the long-time evolution is essentially quasi-neutral and dominated by the ion dynamics.

2. Model

We adopt a one-dimensional geometry along the parallel direction, here denoted x , with corresponding parallel velocity v_x . In the perpendicular plane, the distribution function remains Maxwellian at all times, so that the distribution in the four-dimensional phase space (x, \mathbf{v}) reads as: $F_j(x, \mathbf{v}, t) = f_j(x, v_x, t)M_j^\perp(\mathbf{v}_\perp)$, where $M_j^\perp(\mathbf{v}_\perp)$ is a Maxwellian in the perpendicular veloc-

ity with pedestal temperature T_{ped} and density n_{ped} , and the label $j = i, e$ stands for ions and electrons respectively.

Under these assumptions, the ion and electron evolutions are described by the one-dimensional Vlasov equations for the parallel distribution functions $f_j(x, v_x, t)$:

$$\frac{\partial f_j}{\partial t} + v_x \frac{\partial f_j}{\partial x} - \frac{q_j}{m_j} \frac{\partial \phi}{\partial x} \frac{\partial f_j}{\partial v_x} = g(t) S(x) M_j^{\parallel}(v_x), \quad (1)$$

where $q_j = \pm e$. This collisionless approximation is reasonable for the initial phase of high-energy transients such as ELMs, for which the thermal mean-free-path exceeds the parallel connection length. In the source term [right-hand side of Eq. (1)], $g(t)$ models the pulse temporal profile, $S(x)$ is the spatial profile of the source, and M_j^{\parallel} is a Maxwellian distribution in the parallel velocity. Finally, the electrostatic potential $\phi(x, t)$ is computed self-consistently from the one-dimensional Poisson equation.

The Vlasov equation (1) is solved using an Eulerian method based on a uniform meshing of the parallel phase space (x, v_x) . For the time-stepping, a second-order splitting scheme is used, which solves alternatively the advection in real space and the advection in velocity space. Each advection step is performed using a third-order positive flux-conservative method. In addition, a recently-developed ‘asymptotic-preserving’ numerical scheme [4] allowed us to lift numerical constraints on the time step and grid spacing, which are no longer limited by, respectively, the electron plasma period and Debye length.

3. Numerical results

We performed numerical simulations for a configuration that is relevant to JET type-I ELMs [5]. The spatial profile of the source is given by $S_n(x) = S_0 \cos(\pi x/L_s)$ in the interval $[-L_s/2, L_s/2]$. The source is active in time for a period equal to the ELM duration t_{ELM} . The ELM volume is $V_{\text{ELM}} = L_{\text{pol}} 2\pi R dR$. Here we consider a case with total input ELM energy $W_{\text{ELM}} = 0.4$ MJ, $n_{\text{ped}} = 5 \times 10^{19} \text{ m}^{-3}$, $T_{\text{ped}} = 1.5$ keV, and $t_{\text{ELM}} = 200 \text{ } \mu\text{s}$. The parallel connection length is $L_{\parallel} = 40$ m, and other geometric parameters are taken as follows: $L_s = 25$ m, $L_{\text{pol}} = 2.6$ m, $R = 3$ m, $dR = 0.1$ m.

In addition to the above Vlasov approach, the ELM dynamics was studied using a kinetic particle-in-cell code (BIT1) [2] and a fluid code (SOLF1D) based on a set of modified Braginskii equations [3]. We focus on the energy fluxes measured on the divertor plates. In all kinetic simulations, collisions were neglected and no background thermal plasma was present prior to the ELM event. In the fluid runs, we set to zero the energy exchange terms due to electron-ion collisions, though terms due to self-collisionality are still present (viscous and thermal heat fluxes) [3].

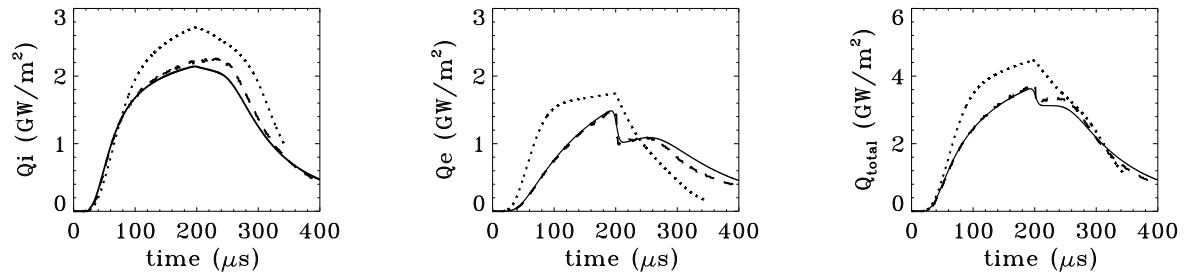


Figure 1: From left to right: electron, ion, and total energy fluxes for various computational approaches: Vlasov (solid line); PIC (dashed line); fluid (dotted line).

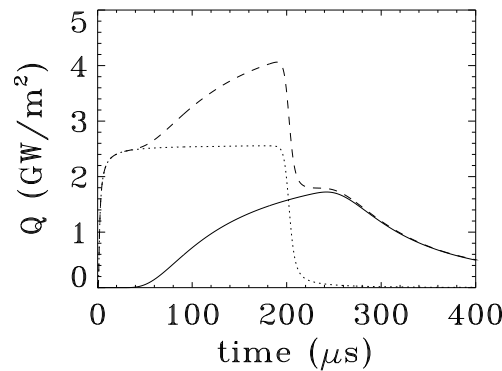


Figure 2: Energy fluxes obtained from the analytical model of Ref. [6]: ion flux (solid line); electron flux (dotted line); total flux (dashed line).

The computed energy fluxes are displayed in Fig. 1 and show a remarkable agreement. In particular, the Vlasov and PIC fluxes turn out to be practically identical. The fluid results appear to slightly overestimate the energy fluxes for both particle species.

We also present the energy fluxes computed using an analytical model that disregards altogether the Coulomb interaction between the charged particles [6]. These results are summarized in Fig. 2. As expected, the analytical model provides a fair approximation for the ion energy flux, but is rather inaccurate for the electrons. Indeed, since the Coulomb interaction is neglected, the two species evolve independently and quasi-neutrality can never be achieved. The more mobile electrons are lost on the divertor plates almost as soon as they have been generated by the source, hence the plateau observed in Fig. 2. A remnant of this plateau is still observed in the fluid simulations (Fig. 1, middle panel), perhaps suggesting that, in the fluid approach, the ions and the electrons are less strongly coupled than in the kinetic simulations.

We now consider the electron dynamics on a much shorter time scale, corresponding to the electron transit time $\tau_{\parallel} = L_{\parallel}/v_{Te}$ which is approximately $2.4 \mu\text{s}$ in our case. An early burst of electrons is observed on this time scale, as can be seen from Fig. 3. This burst is due to a bunch of

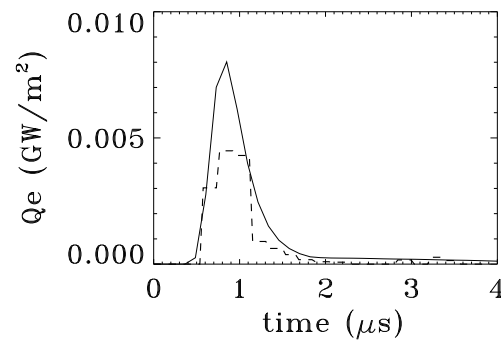


Figure 3: *Electron energy flux at short times, computed with the Vlasov code (solid line) and PIC code (dashed line).*

electrons escaping the attraction of the ions and reaching the plates before quasi-neutrality can be established [1]. This electron burst was not observed in the fluid simulations, thus confirming that it is indeed a kinetic effect. The difference between the PIC and Vlasov results may be due to a sampling error, as very few particles are present in the tail of the Maxwellian distribution.

In summary, we have presented numerical simulations of the SOL transport using a novel Vlasov code. The results are in good agreement with those obtained with other approaches, namely a PIC and a fluid code, as well as analytical results based on a free streaming model. A detailed comparison for more realistic scenarios – including collisions and a background pre-ELM plasma – is currently underway [7].

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